Robust CO_2 Plume Imaging using Joint Tomographic Inversion of Seismic Onset Time and Distributed Pressure and Temperature Measurements

Project Number **DE-FE0031625**

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U.S. Department of Energy

National Energy Technology Laboratory

Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

August 26-30, 2019

Presentation Outline

- Why are we doing this?
  - Benefits to the program
- How are we doing this?
  - Project overview and methodologies
- Accomplishments to date
  - Application to a post-combustion CO_2 WAG Pilot
- Summary and next steps

Benefit to the Program

- **Program goals being addressed**
  - *Development of modeling and monitoring methods, tools, technologies that improve the certainty about the position of the CO_2 plume over time*
- **Project benefits statement**
  - Provide a practical & cost-effective methodology for CO_2 plume delineation using routine pressure/ temperature measurements + geophysical monitoring
  - Facilitate (near) real-time monitoring of CO_2 plume migration in field projects needed to meet current regulatory requirements

Project Overview:
Goals and Objectives

- Develop and demonstrate a rapid and cost-effective methodology for spatio-temporal tracking of CO_2 plumes during geologic sequestration
  - ***Pressure and temperature tomography***: Use pressure & temperature arrival time data to infer spatial distributions of CO_2 plume
  - ***Integration of seismic onset time***: Improve the seismic monitoring workflow through the integration of '***onset***' times
  - ***Joint Bayesian inversion and field validation***: Efficient Bayesian framework for probabilistic data integration validated using data from ongoing field projects (Petra Nova Parrish CCUS project, Texas)

Methodology

CO_2 Plume Imaging: Key Elements

- Recasting Fluid Flow Equations as Tomographic Equations
  - High frequency asymptotic solution
- Utilization of the Seismic Onset Time Concept
- Parsimonious Representation of Geologic Heterogeneity
  - Ill-posed inverse problem, needs regularization
  - Image compression via basis functions
- Data Integration and Image Updating
  - Multi-objective optimization and Inverse Modeling

Methodology

Asymptotic Approach: Fluid Fronts vs. Wave Fronts *

* Fatemi and Osher, 1995; Vasco and Datta-Gupta, 1999; 2016

- High frequency solution to the flow and transport equation mimics the one usually found in wave propagation
- We can exploit the analogy between the propagating fluid front and a propagating wave
- The trajectories or flow paths associated with the fluid front are similar to rays in seismology/optics
- Provides an efficient formalism for plume imaging using reservoir dynamic response

Methodology

Asymptotic Solution: Diffusivity Equation

- Diffusivity equation in heterogeneous medium

$$\phi(\mathbf{x})\mu c_t \frac{\partial P(\mathbf{x},t)}{\partial t} = \nabla\cdot(k(\mathbf{x})\nabla P(\mathbf{x},t))$$

- Transform to Fourier domain

$$\phi(\mathbf{x})\mu c_t(-i\omega)\tilde{P}(\mathbf{x},\omega) = k(\mathbf{x})\nabla^2\tilde{P}(\mathbf{x},\omega) + \nabla k(\mathbf{x})\cdot\nabla\tilde{P}(\mathbf{x},\omega)$$

- High frequency asymptotic solution leads to a propagation equation for pressure 'front':

$$\boxed{\sqrt{\alpha(\mathbf{x})}\left|\nabla\tau(\mathbf{x})\right| = 1} \quad \text{where} \quad \alpha(\mathbf{x}) = \frac{k(\mathbf{x})}{\phi(\mathbf{x})\mu c_t}$$

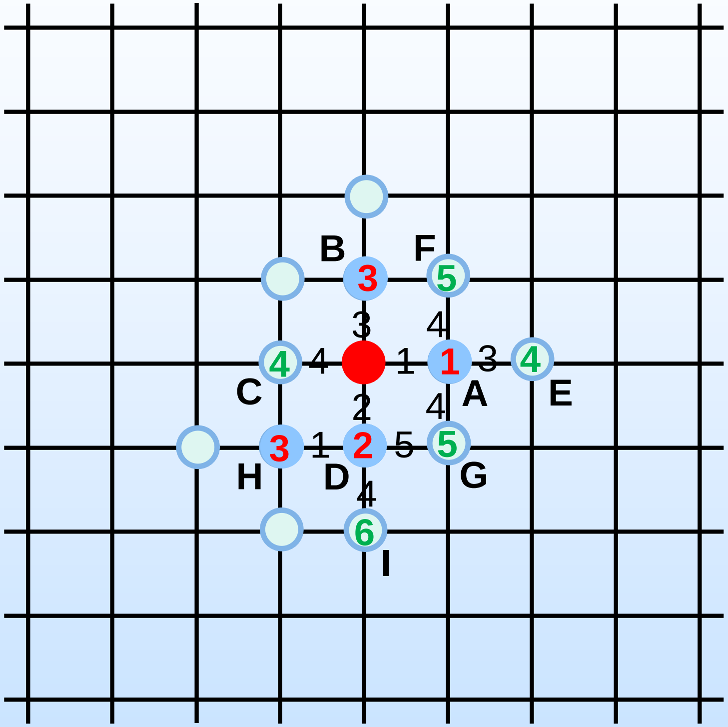
Eikonal Equation

The Eikonal equation can be solved efficiently using the Fast Marching Method (Sethian, 1996)

Methodology

Solution to Eikonal Equation

- **Fast Marching Method**: efficient method to solve the Eikonal equation (Sethian 1998,1999)
- **Dijkstra's Method** (1959): computing the shortest path on a network
- **Single-pass:** solution can be constructed sequentially from small τ to large τ

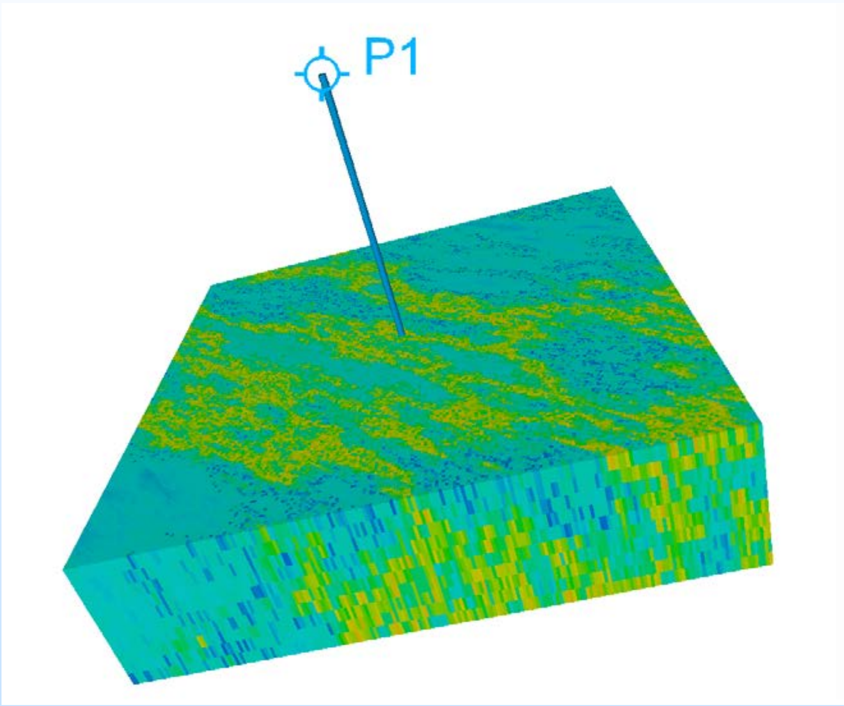


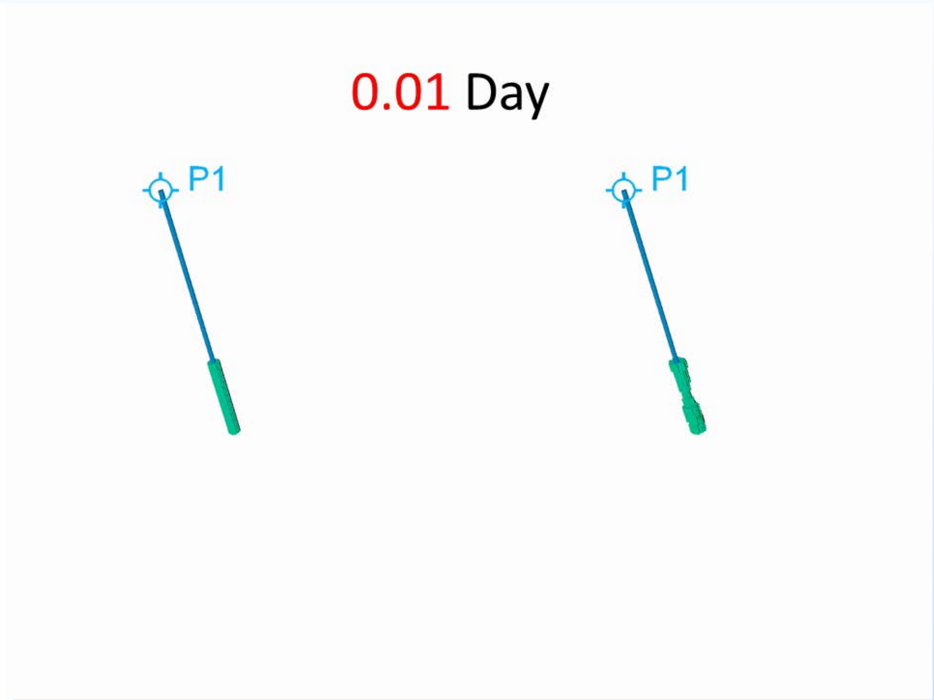
$$\delta\tau(\vec{x}) = \sqrt{\frac{\phi(\vec{x})\mu c_t}{k(\vec{x})}}\delta r$$

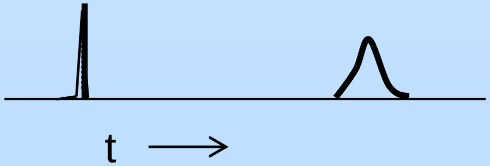
Technology used in Google Maps

Methodology

Pressure 'Front' Propagation



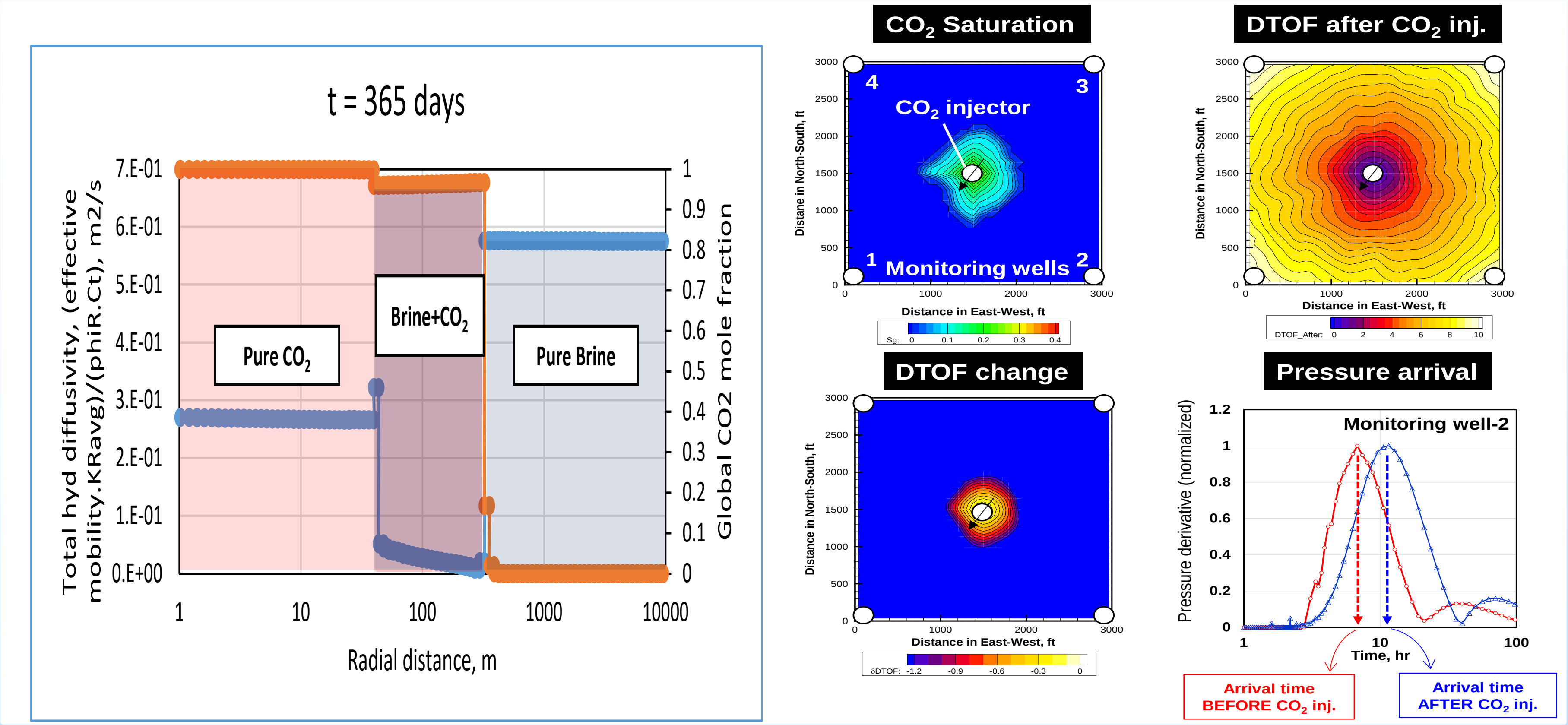




Methodology

Pressure ‘Arrival Time’ Tomography

(He, Dattagupta, Vasco, 2006;Brauchler et al., 2007; Hu et al., 2015)



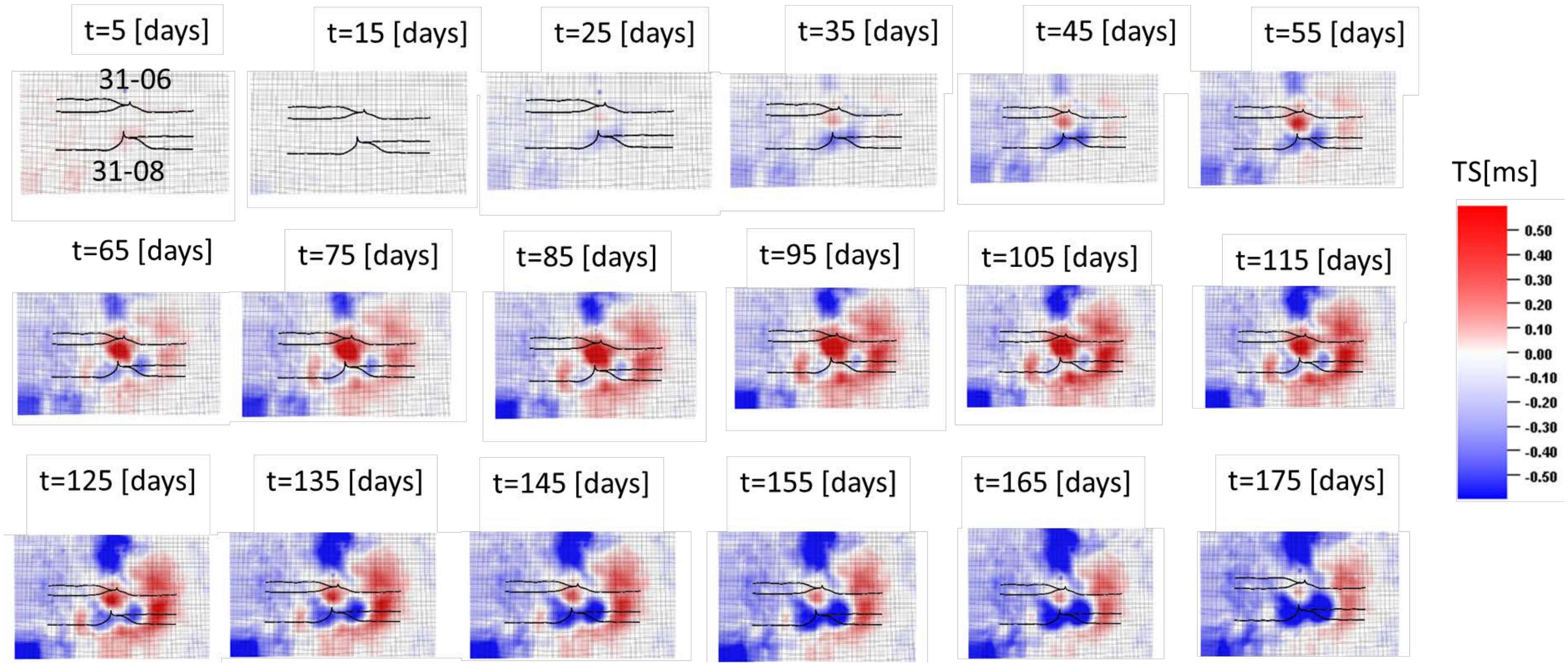
Methodology
Temperature Tomography

- Analogous Approach to Pressure Tomography
- **Assumption** – The diffusive time of flight gradients are aligned with temperature gradients
  - 3D to 1D equation for temperature propagation
- Proof of concept presented (SPE Journal, Dec. 2016)

Methodology

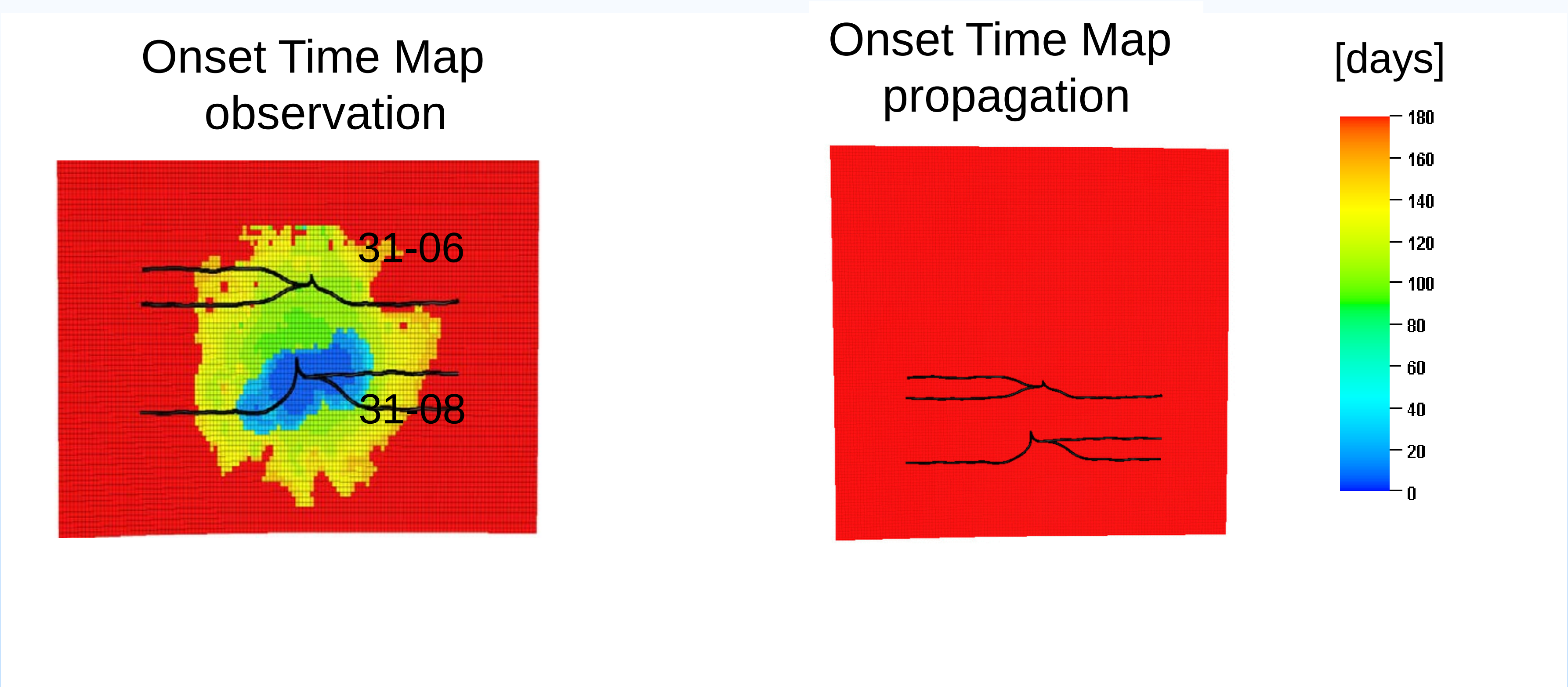
Seismic Monitoring via Onset Times

Two-Way Time Shift Maps: Peace River (Hetz et al., 2017)



Methodology

Onset Time Map: Better Representation of Time Lapse Seismic Data

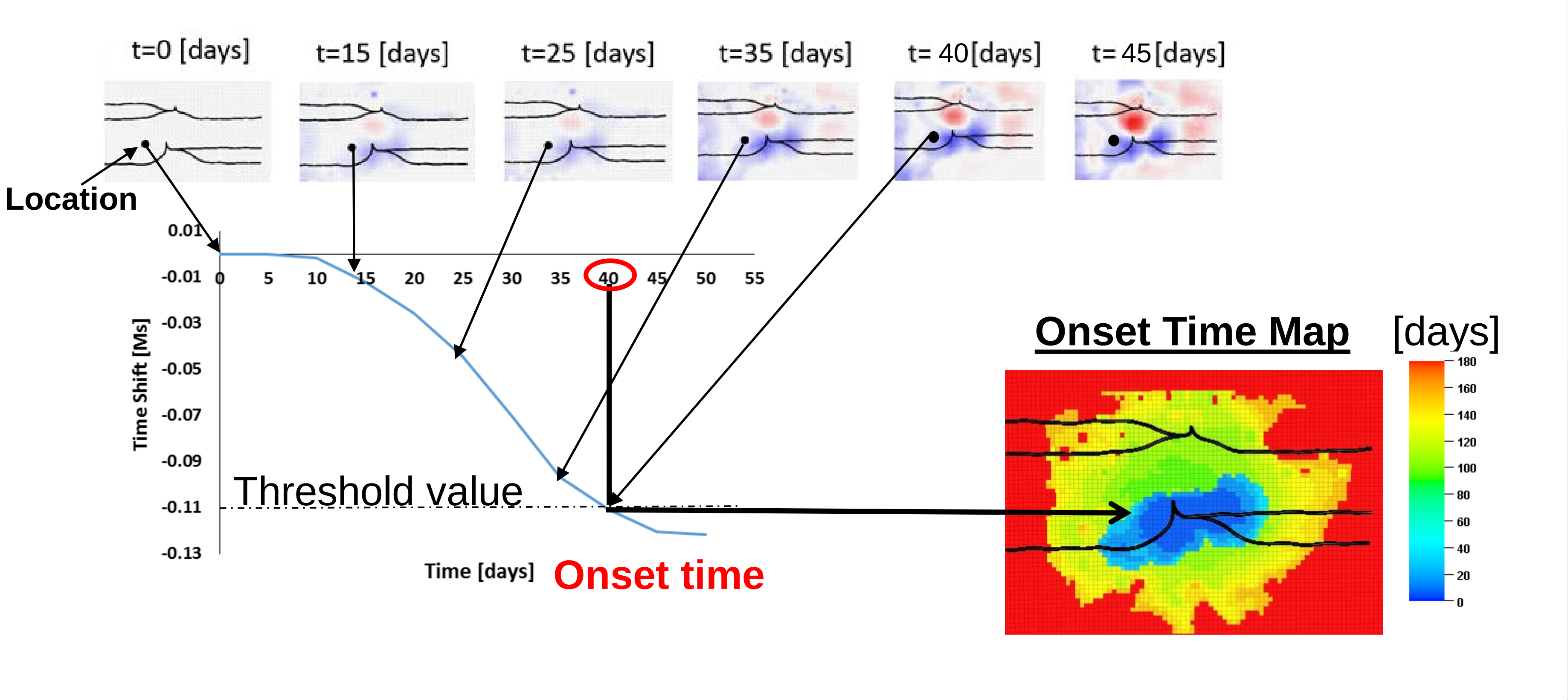


Reduces multitude of time-lapse surveys into a single set of onset time map

Methodology

Time Shift Maps to Onset Time Map

- The calendar times at which geophysical observations begin to deviate from their initial or background value (Vasco,2015)



Methodology

Seismic Monitoring Using Onset Time

- Efficient integration of frequent time-lapse seismic surveys through substantial data reduction
- More robust: Less sensitivity to petroelastic model compared to amplitude inversion
- Rapid convergence: quasilinear inverse problem

Applicability to infrequent seismic surveys needs to be investigated

Methodology

Data Integration and Model Updating: Issues

- Diverse Data Types
  - Scale, resolution and precision
  - Potentially conflicting
- Poorly constrained
  - Sparse data, large parameter space
- Multi-scale, Multi-objective Inverse Problem
  - Pareto Optimal Solution

Accomplishments to Date: Year 1

- CO_2 Plume Tracking at Petra Nova CCUS Pilot – Project
  - *Fuel* 255 (2019) 115810
- Saturation Imaging Seismic Onset Time: Impact of Survey Frequency
  - *SPE 196001* (ATCE 2019)
- Application of ensemble learning for machine-learning based data integration
  - *URTeC* 2019-929 (2019)

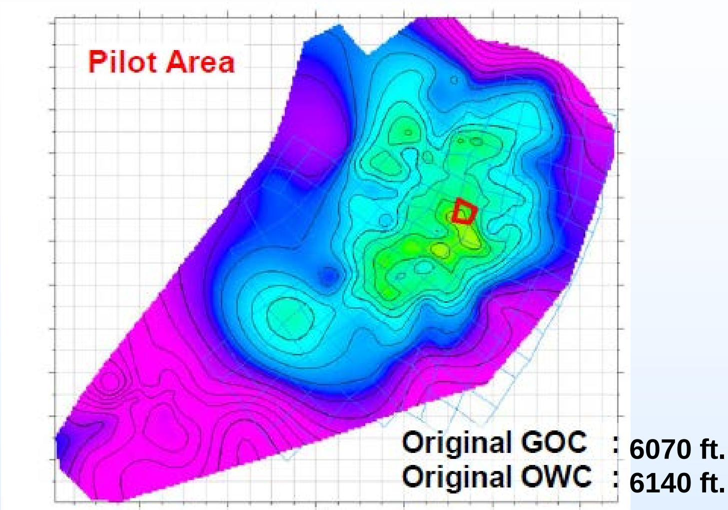
Background: Petra Nova CCUS Project

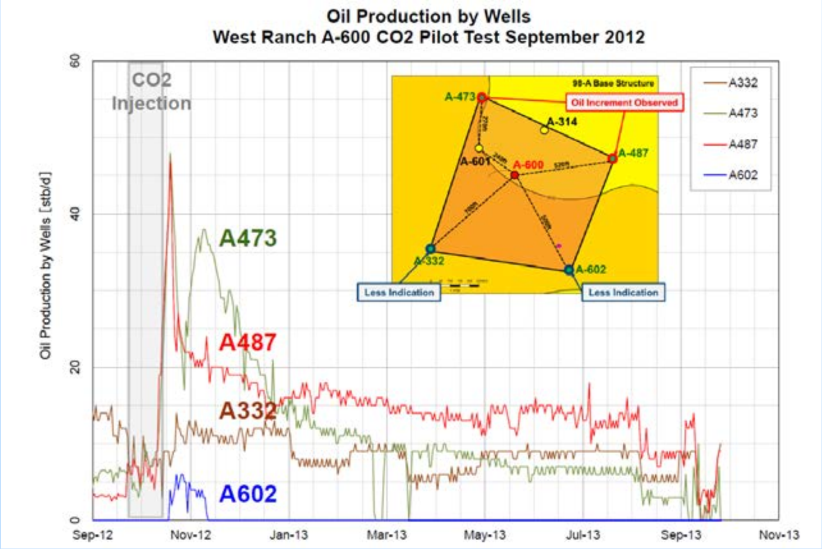
Power Plant

West Ranch
Oil Field

- World's largest post-combustion CO_2 capture, EOR and storage project
- NRG/JX Nippon partnership
- Captures more than 90% of CO_2 from a 240 MW flue gas stream (~ 5,000 tons of CO2 per day)
- Captured CO_2 is utilized for EOR
- 60 MMSTB of oil is estimated to be recoverable from EOR operations

West Ranch Field 98-A CO2 Pilot
September 2012





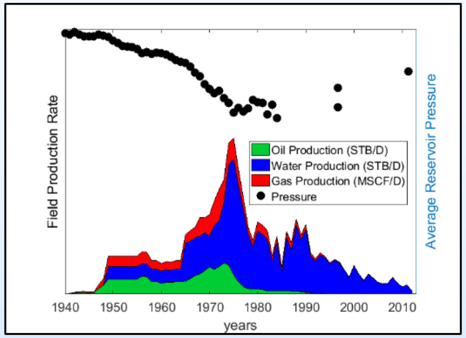
- CO2 Pilot conducted in center of 98-A
- 16 acre inverted five-spot
- Single injector, four producers and two observation wells
- 230MMSCF CO2 injected for 20 days followed by water
- Clear oil response observed in two producers

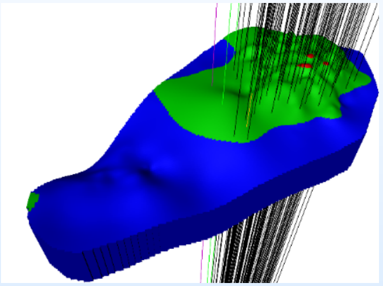
Goal:* *Infer CO_2 plume movement based on the production response and CO_2 breakthrough

Previous Work: Field Model Calibration

(SPE Reservoir Engineering, January 2019)

Reservoir Model

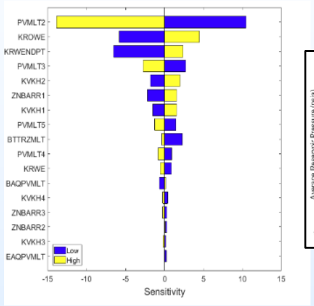


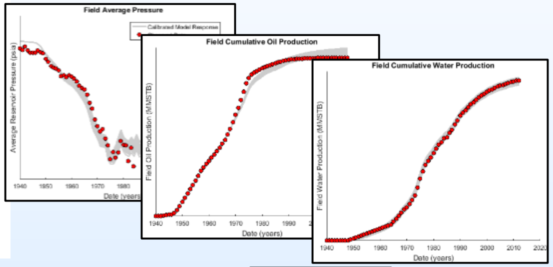


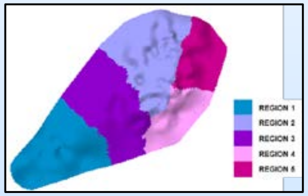
Size:	$10km \times 5km$
Thickness:	140ft
Geologic Grid:	$253 \times 212 \times 140$
Active Cells:	$3{,}000{,}000$
Perm Range:	$0.5 - 40{,}000\text{mD}$ (Very heterogeneous)

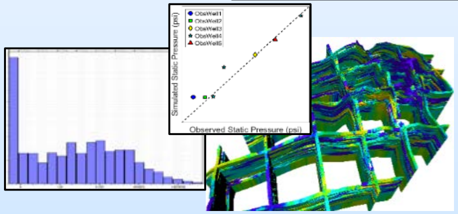
- >120 wells drained over a period over 75 years
- No well completion data; limited well production data

Hierarchical Model Calibration







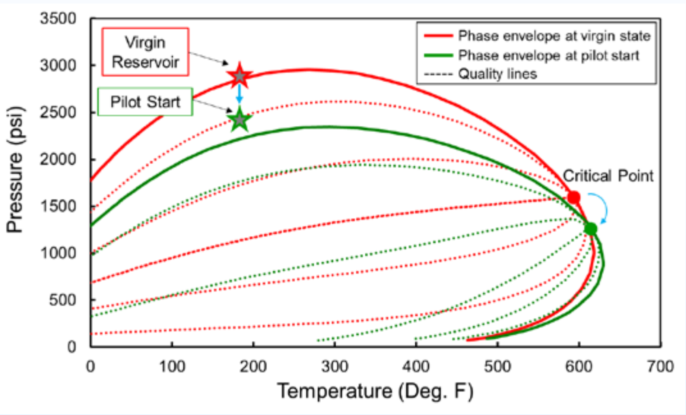


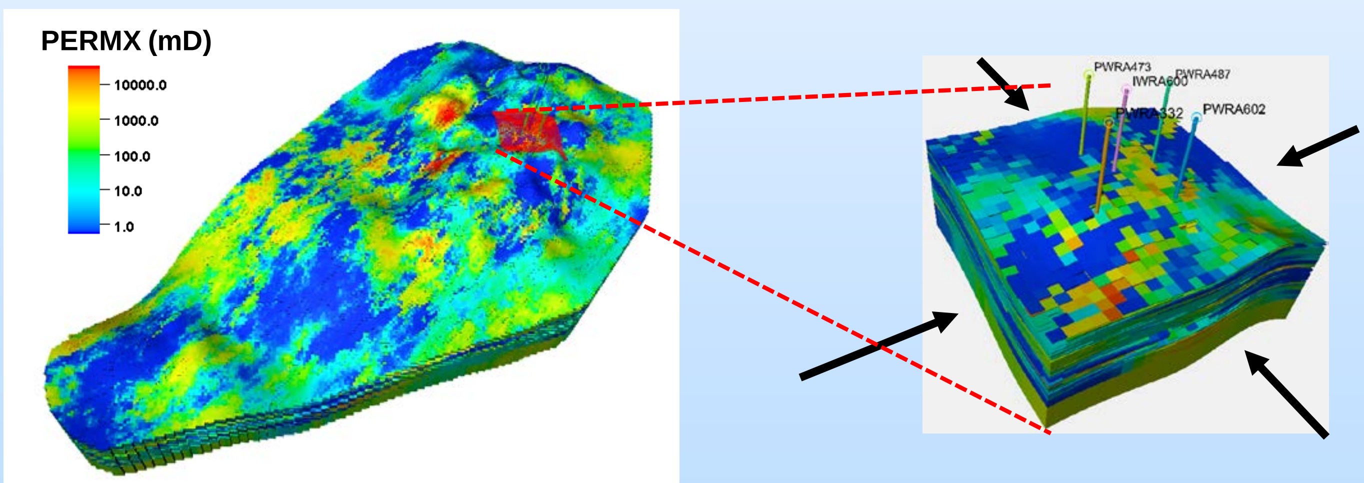
Next Steps

- Initialize pilot model from calibrated field model
- Integrated pilot production data
- Optimize CO_2 EOR design, as an optimal parametric design for entire field

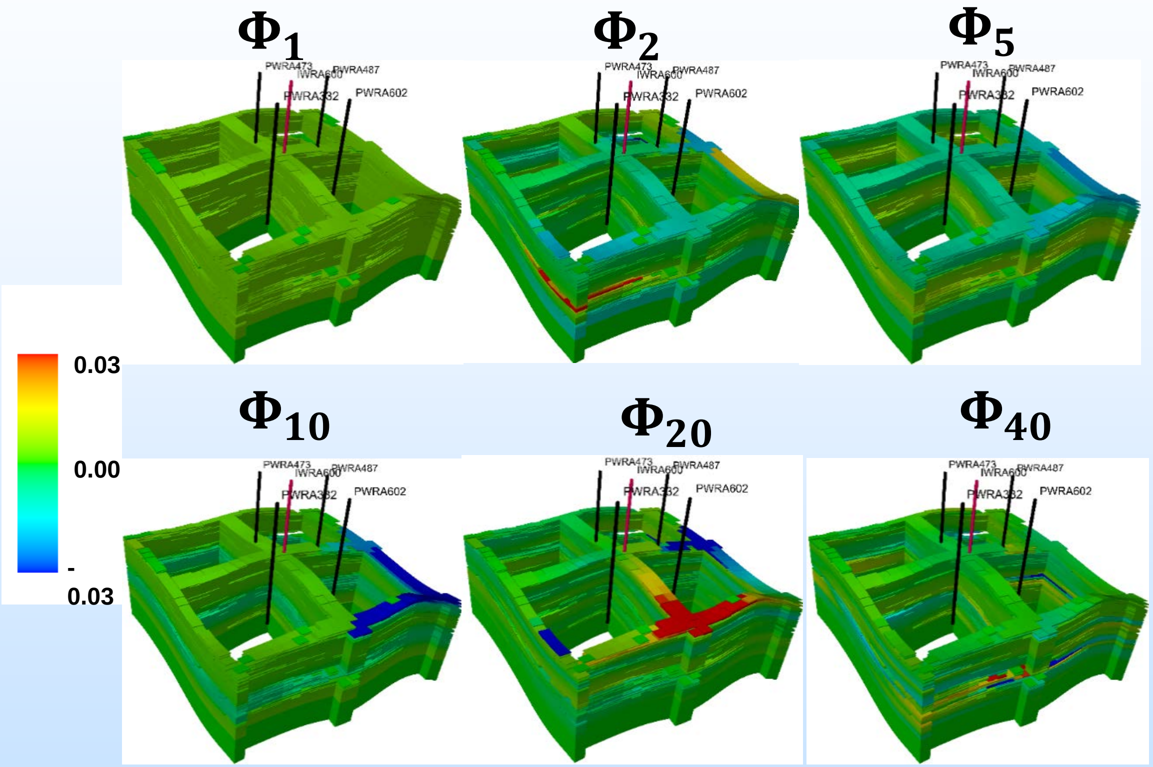
Sector Model from Full Field Model

- Fully compositional model
- Pilot model initialized from the full-field model
- Boundary fluxes from full field model were imposed





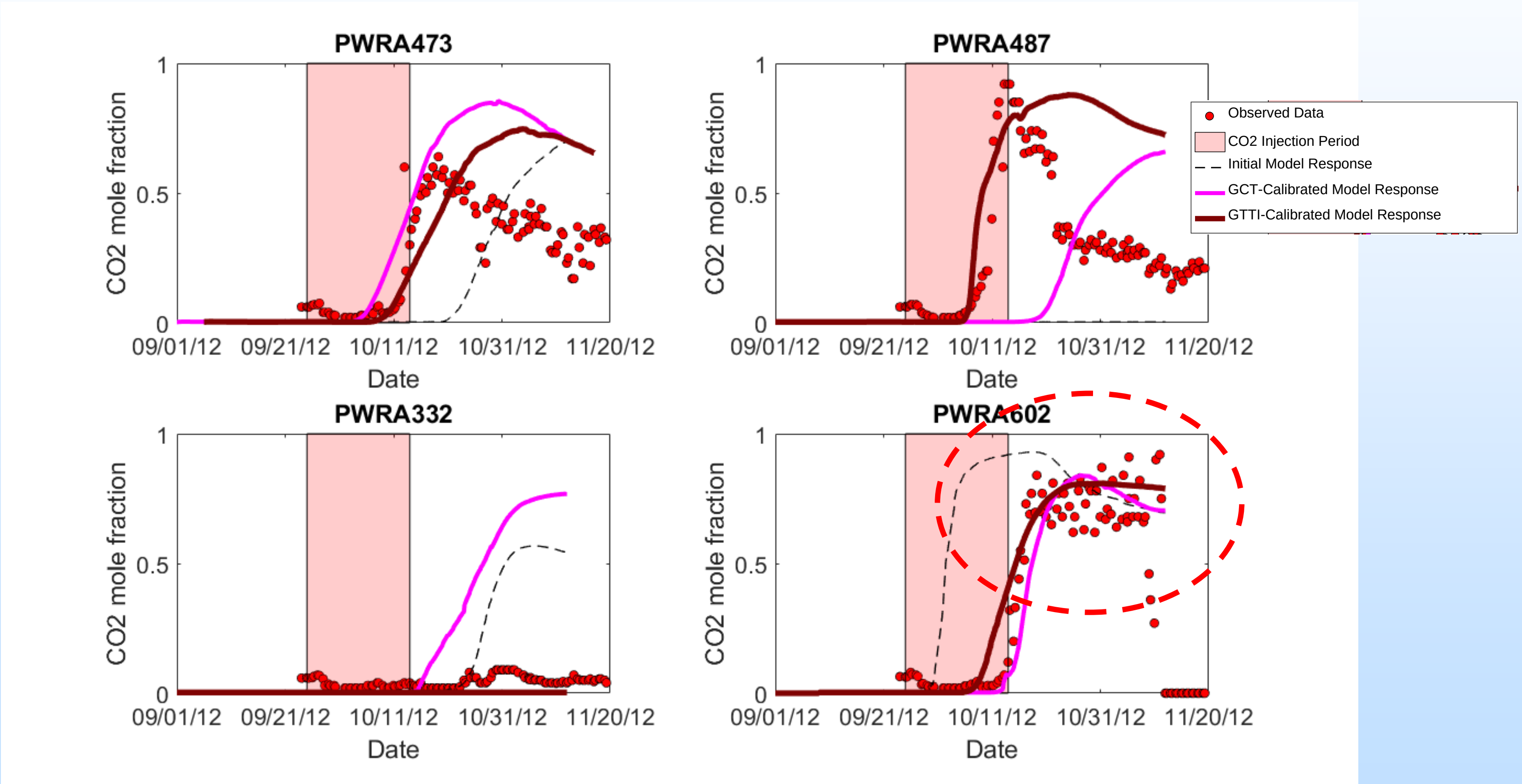
Model Parameterization & Objective Function



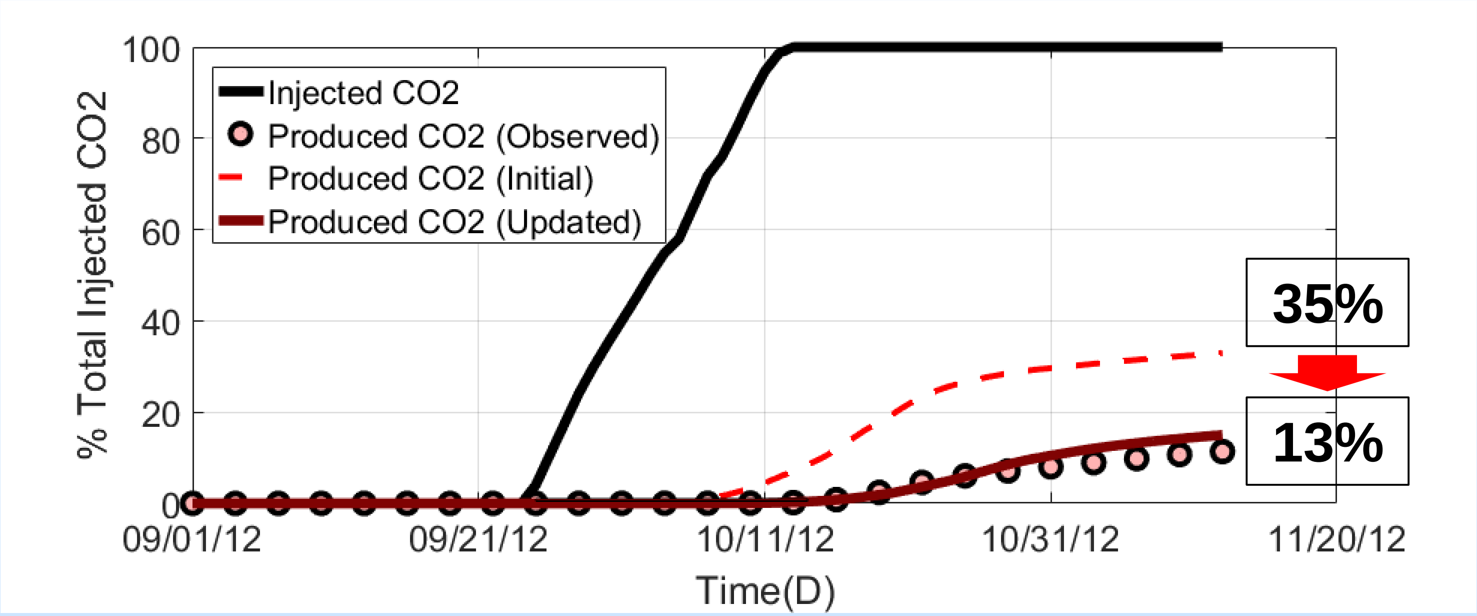
Parameter	Low	Mid	High
40 Basis Functions	-50	0	50
Krw Exponent	1.5	3.0	5.0
Krow Exponent	1.2	2.0	5.0
Krog Exponent	1.5	2.0	5.0
Krg Exponent	1.2	2.0	4.0
Krw Endpoint	0.2	0.5	1.0
Krg Endpoint	0.5	0.8	1.0

Objective = ***In***(WOPR_Misfit) + ***In***(WGPR_Misfit)
+ ***In***(WWPR_Misfit) + ***In***(WBHP_Misfit)

Model Calibration Results: CO_2 Mole Fraction

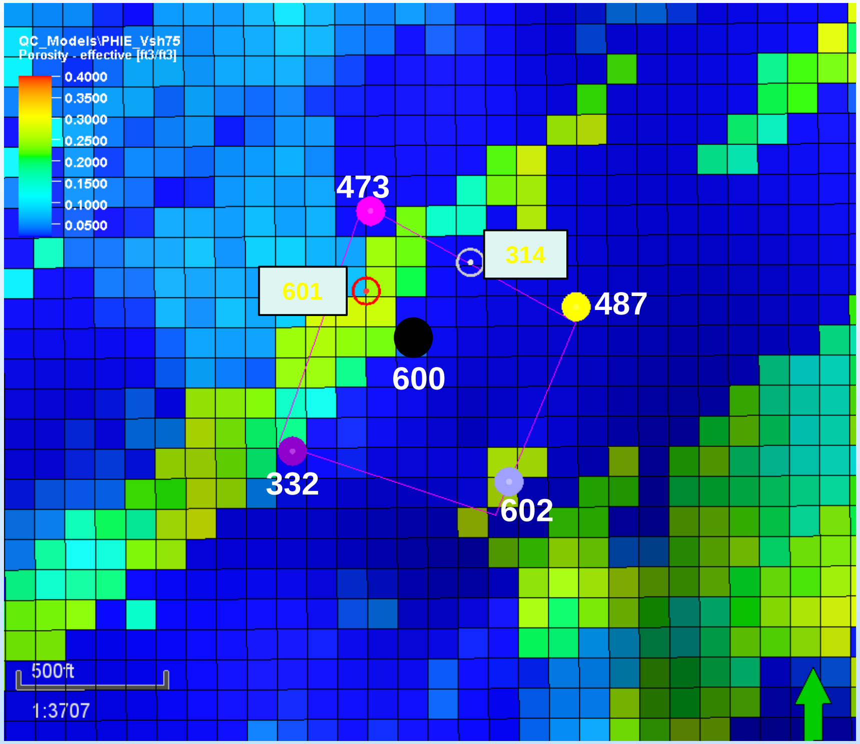


CO_2 Recovery Comparison

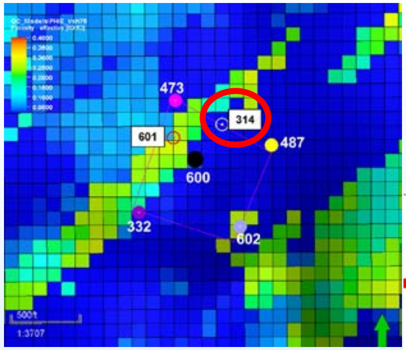


Model Validation: Saturation Logs Comparison

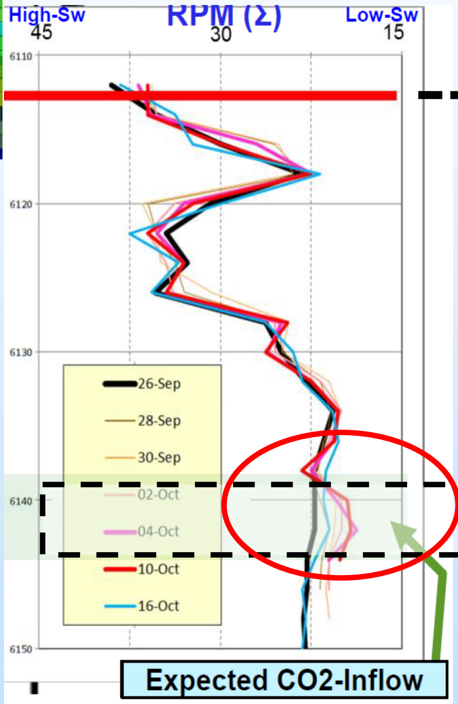
- **600** is the Injector
- **473, 487, 602** and **332** are producers
- **314** and **601** are monitor wells



Saturation Logs Comparison: Well 314

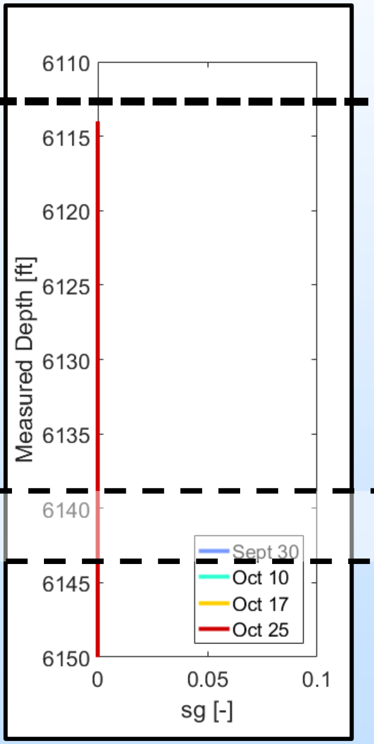


OBSERVED

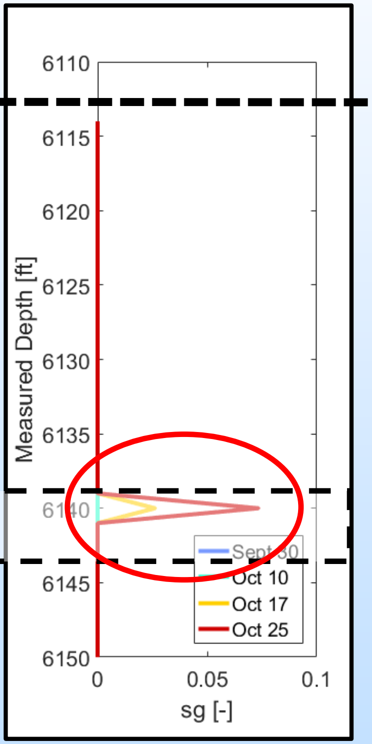


TO
P

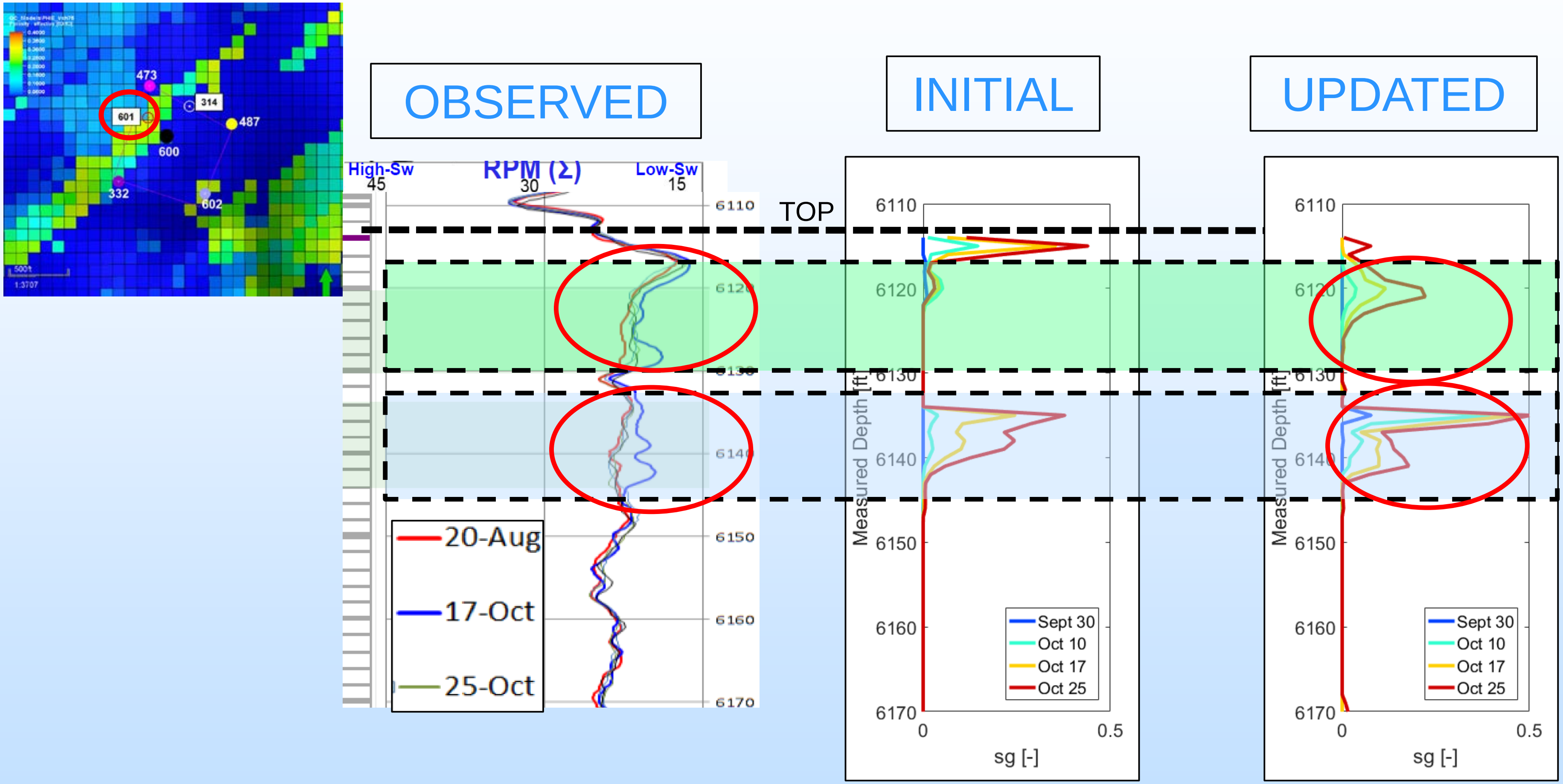
INITIAL



UPDATED



Saturation Logs Comparison: Well 601



CO_2 Plume Profile Comparison

Next Steps

- Development and testing of temperature tomography based plume detection for CO2-oil-gas-brine-systems
- Development and testing of joint inversion of temperature and pressure data for plume detection for CO2-oil-gas-brine-systems
- Further refinement of seismic onset time based inversion: survey frequency and attribute selection
- Field validation of the numerical tomographic inversion using data from ongoing CO_2 injection projects (e.g., Petra Nova CCS)

BACKUP

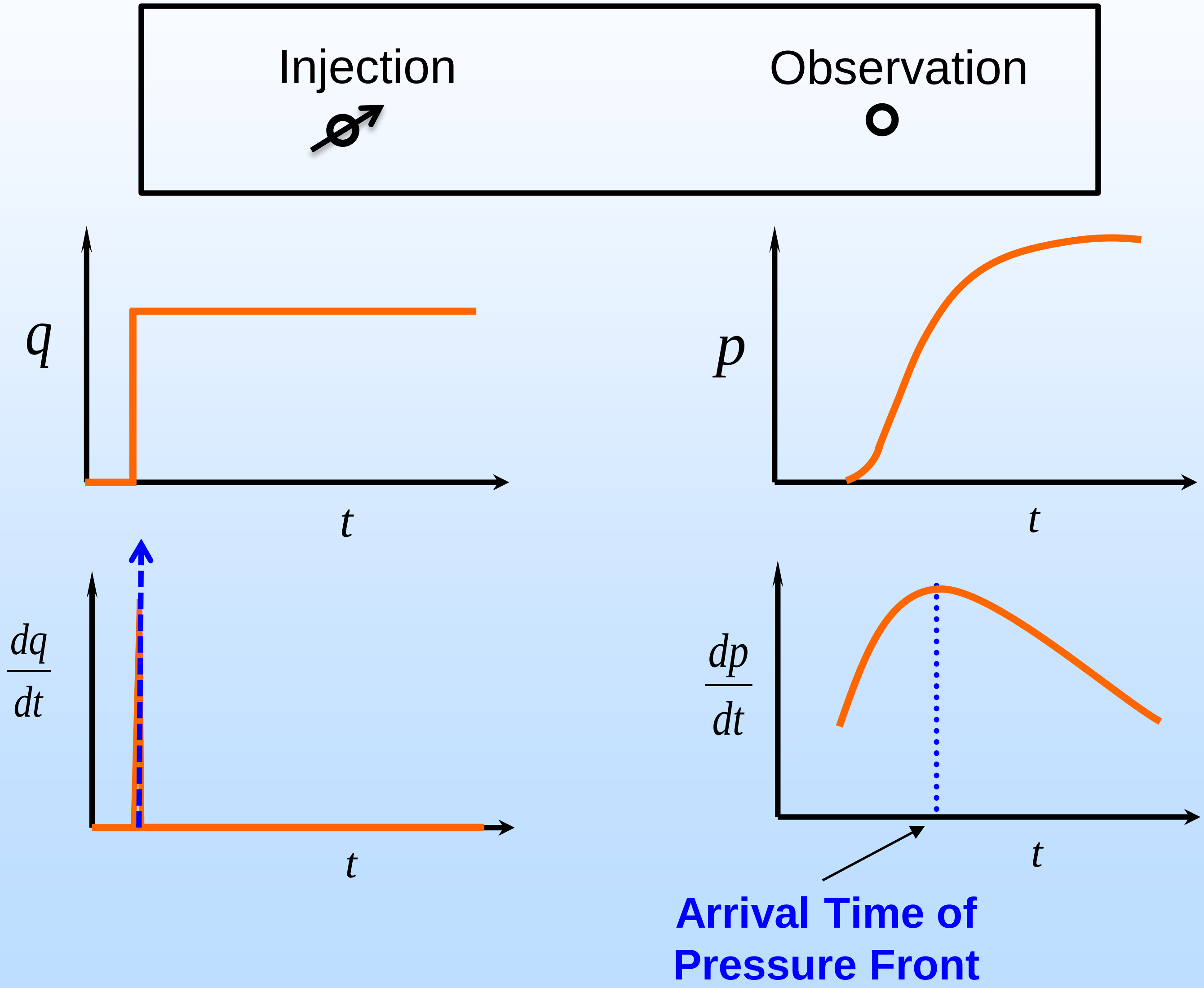
Expected Outcomes

- Advanced CO_2 plume mapping protocols using novel forward and inverse modeling techniques to:
  (a) reduce cost and uncertainty
  (b) satisfy regulatory requirements
  (c) provide continuous monitoring and long-term durability
  (d) cover a large area with improved accuracy

- **Key elements** are:
  (a) novel pressure and temperature tomography using the Fast Marching Method (FMM)
  (b) analysis of time lapse seismic data using a novel ‘seismic onset time’ approach to detect fluid front propagation
  (c) data assimilation and uncertainty assessment
  (d) field validation of the methodology

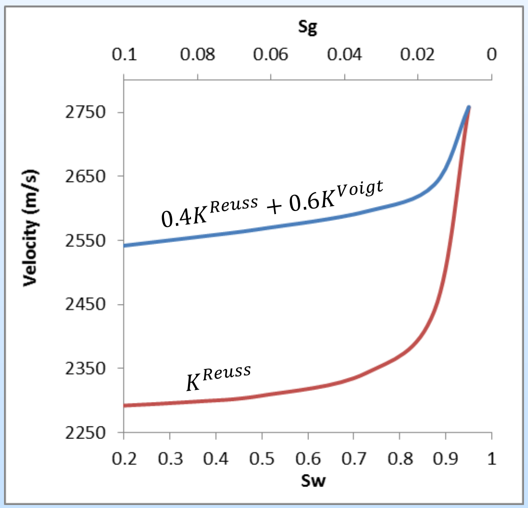
Methodology

Arrival Time of Pressure 'Front'



Onset Time is Less Sensitive to the Petro Elastic Models

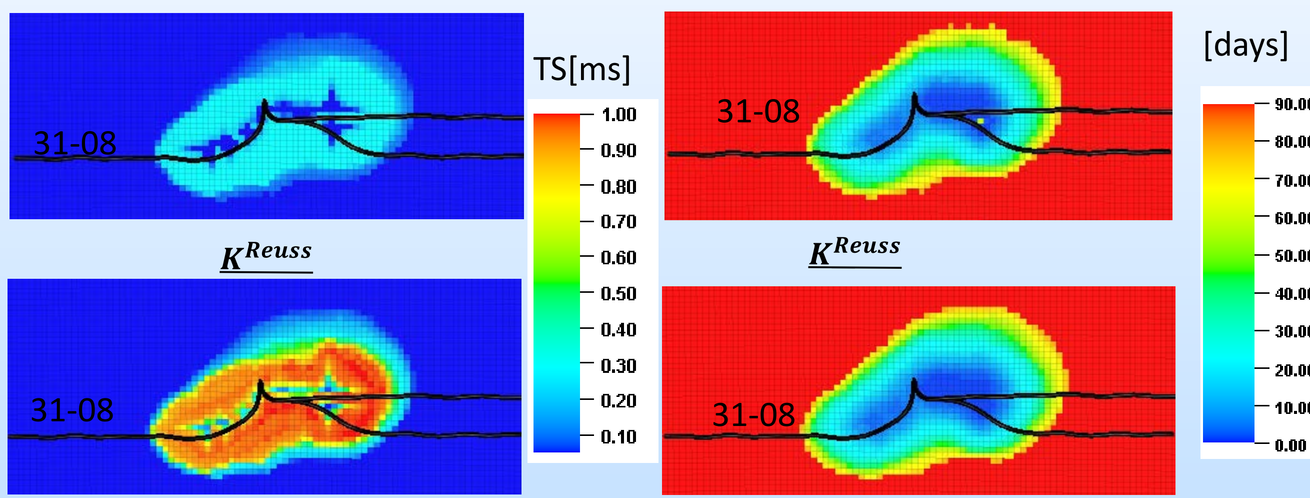
Velocity as a function of saturations for different averaging methods



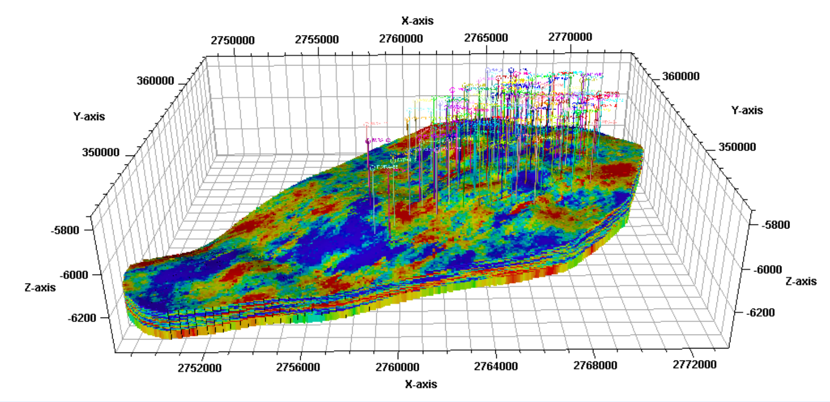
Seismic response over the first 85 days of the CSS (Top View)

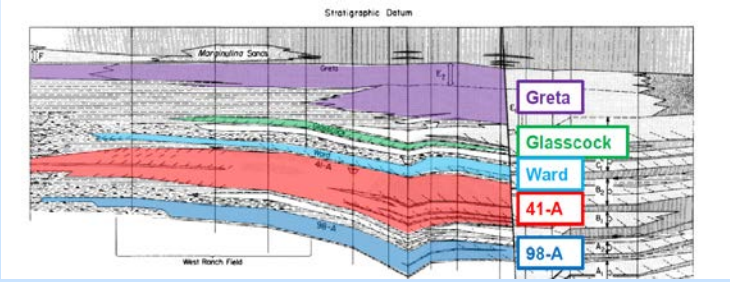
Time Shift **Onset Time**

$\mathbf{0.4K^{Reuss} + 0.6K^{Voigt}}$



West Ranch Field : Background





- Highly heterogeneous (Fluvial Sand)
- Perm Range: $0.1 - 40{,}000\ (\mathrm{mD})$
- Severe vertical permeability anisotropy due to intermediate shale barriers (Dykstra-Parsons coefficient > 0.9)
- >120 wells drained for a period over a 75 years